Underwater Glider Dynamics and Control

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LONG-TERM GOALS

My long-term goal is to help improve versatility of underwater gliders as individual or networked platforms for ocean sampling and other applications by contributing to the development of a methodology for designing and analyzing high-performance, cost-effective underwater glider controllers.

OBJECTIVES

In this work, we build on our earlier results and accomplishments in understanding, modeling and controlling underwater glider dynamics (YIP Grant # N00014-98-1-0649). The focus is on dedicated gliding vehicles that have the ability to change mass (or volume) for buoyancy control and to redistribute mass (and possibly control a rudder) for attitude control. The framework consists of a dynamical systems model of underwater gliding vehicles together with techniques for generating and controlling glide maneuvers in the presence of uncertainty. The central objectives are as follows:

1. Modeling and verification of underwater glider dynamics in two and three dimensions. An important challenge here will be to build on our existing 3D dynamic model to best include hydrodynamic forces on a rigid body with wings in water. In this context we will seek to make the best use of experimental data from existing full-scale gliders as well as our own laboratory-scale underwater gliders.

2. Nonlinear control design for underwater glider stabilization and tracking in two and three dimensions. A key challenge is to design control algorithms that are consistent with the constraints and limits on control actuation (and sensing) in a buoyancy-propelled underwater glider. We will focus on gliders with fixed external surfaces, as well as those with a rudder, which can control buoyancy, e.g., through ballast change, and can control center of gravity, e.g., by means of mass redistribution.

3. *Coordinated control strategies for multiple vehicles and realization of these strategies on a network of buoyancy-controlled underwater gliders*. Significant challenges include designing coordination algorithms that are robust to failure and scalable with the number of vehicles. Further, the realization of techniques for glider dynamics will need to accommodate the very specialized way that buoyancy-controlled gliders can be made to maneuver.

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14. ABSTRACT
My long-term goal is to help improve versatility of underwater gliders as individual or networked platforms for ocean sampling and other applications by contributing to the development of a methodology for designing and analyzing high-performance, cost-effective underwater glider controllers.

15. SUBJECT TERMS

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4. *Demonstration and testing of glider control strategies*. We plan to test and demonstrate our strategies on gliders as part of the AOSN-II Monterey Bay Field Experiment in the summer of 2003, in experiments in the Bahamas, and elsewhere. We will also perform experiments on our laboratory-scale gliders.

5. *Participation in the ONR Glider Systems Study.* The aim of the ONR Glider Systems Study is to determine the wide range of possibilities for underwater glider technologies and potential applications. This study is a conceptual one of relatively broad scope in terms of platform scale and configuration; rapid approximate methods are to be used to develop rough performance envelopes. We aim to contribute to glider concepts, configurations, models and analyses.

APPROACH

The approach and methodologies employed, corresponding to the above objectives, are as follows:

1. We have derived a dynamic glider model that describes a glider with simple body and wing shape (Leonard and Graver [2001]). Control is applied to two point masses inside the vehicle: the first point mass has variable mass but fixed position while the second point mass has fixed mass but variable position relative to the center of buoyancy. The model describes the nonlinear coupling between the vehicle and the shifting and changing mass. This model was derived for a glider in 3D and then specialized to motion in the vertical plane. Standard methods are used to extend the model to include a rudder. We use historical and new experimental data together, our own wind tunnel testing results together with theory and aerodynamic reference data to develop an accurate hydrodynamic model for a class of operational gliders. Systems identification methods have been used (and in some cases derived) to enable this effort. Wind tunnel testing has already been performed for a scale model of our laboratory glider ROGUE (Figure 1) in order to determine a lift and drag model (Graver et al [1998]).

Figure 1: The Princeton laboratory-scale underwater glider, ROGUE. The hull is 18 inches long.

2. We have designed linear controllers and observers for stabilization of steady glide paths in the vertical plane (Leonard and Graver [2001], Graver and Leonard [2001]). These control laws already have the potential to make improvements over current practice on operational gliders. In principle, these model-based, feedback controllers require less experimentation and tuning and provide more robustness to fouling, payload changes and other uncertainties as compared to current techniques. Additionally, a dynamic observer estimates states that can be used to determine horizontal glider motion rather than the current methods that rely on assumptions of constant angle of attack. This can

provide significant improvement to dead reckoning, to determination of flow velocity over glide cycles as well as to control. We use nonlinear methods to derive control laws that are more versatile and overcome some of the limitations of approaches based on linearization. For example, nonlinear controllers could yield larger regions of attractions (i.e., stability guarantees on more global behavior). The approach makes use of energy-based Lyapunov function design for proving stability of mechanical systems that we have recently developed with colleagues for underactuated systems (see, for example, Bloch, Leonard and Marsden [2001]). The method of controlled Lagrangians is a control synthesis approach that provides a control law that modifies system energy so that the motion of interest is stable. The method is particularly well suited to underactuated systems, i.e., systems like underwater gliders that have fewer control inputs than system degrees of freedom. To make this method relevant to mechanical systems with hydrodynamic forcing (lift and drag), we make use of a useful interpretation and analysis of the phugoid mode equations together with a singular perturbation analysis. The singular perturbation analysis allows extension to higher-dimensional dynamics. We will also consider optimal motion planning approaches for the glider (see, for instance, Chyba, Leonard and Sontag [2001]).

3. We further develop our distributed approach to coordination of autonomous vehicle networks with a particular focus on realizing these strategies on underwater gliders which are underactuated and constrained systems. In earlier work we have developed coordinated and cooperative control strategies for fully actuated point mass vehicle models that make use of artificial potentials and virtual leaders (see, for example, Leonard and Fiorelli [2001] and Ogren, Fiorelli and Leonard [2002]). Here, we investigate how to extend this work so that we can guarantee network stability and performance for our underwater glider dynamics. We consider a model in which the individuals move at a constant speed and the control law determines the steering. The approach involves making use of results from the literature on coupled oscillators. We also look at coordination of networked mechanical systems which have unstable dynamics using the method of controlled Lagrangians.

4. We adapt our model to operational gliders so that we can perform system identification, estimation of states, improved dead reckoning, improved control and network coordination in the AOSN-II Monterey Bay Field Experiment in Summer 2003 as well as in experiments run in preparation for this experiment. These experiments are done in close collaboration with Dave Fratantoni at WHOI who operates a fleet of gliders.

5. We use our modeling and analysis tools to examine the process and choices involved in glider sizing and hydrodynamic design. We also analyze glider control systems for ability to cope with the challenging dynamic environment and the actuation and sensing constraints. The controller should be robust with respect to environmental uncertainties and at the same time it has to be optimal in the sense of power consumption and accuracy.

This project is led by N. Leonard (PI). R. Bachmayer (Research staff, Princeton) has played a key role in all aspects of this project, notably on the experimental and simulation side. J. Graver and P. Bhatta (graduate students) work on the gliding modeling, dynamics and control laws. E. Fiorelli (graduate student) designs and studies coordinating control laws for multiple underwater gliders. R. Sorenson (Tech. staff, Princeton) works on our laboratory-scale glider ROGUE and multi-vehicle test-bed.

WORK COMPLETED

We have extended and analyzed our glider dynamic model in a number of ways and have adapted it to the Slocum glider. We ran preliminary wind tunnel tests with a scaled version of the Slocum. In January 2003, we participated in a glider cruise in the Bahamas (in collaboration with Dave Fratantoni, WHOI, who was PI on this cruise) and ran experiments that involved steady straight and turning glides and various operational/control modes. We used the experimental data to identify model parameters in the glider's hydrodynamic model (in steady state). We found an asymmetry in the upward versus downward steady glide drag term. This was understood with further analysis and estimation of an offset in the glider buoyancy trim. We performed a preliminary study of the controller design for the Slocum during and after the Bahamas cruise. Some of our suggestions for control software modifications to improve glider performance have been implemented by Webb Research Corp. We also participated in the Canadian/U.S. Seaweb cruise in the Gulf of Mexico in February 2003 and collected additional excellent glider data.

We have developed a method for analyzing stability for nonlinear glider dynamics using the original phugoid mode equations. These equations describe a falling body with lift. We have adapted this model for a body with lift in the water and have defined a Hamiltonian model for this system of equations. This allows for the derivation of a Lyapunov function to prove stability. Using singular perturbation analysis, we have proved how results for the simplified phugoid mode dynamics extend to higher dimensional glider dynamic models.

We have adapted our coordinated and cooperative control strategies for the operational setting in AOSN-II and have participated in the entire field experiment in Monterey Bay from mid July 2003 until early September 2003. We ran a series of coordinated experiments with these gliders thus amassing considerable data for further analysis. We have developed steering control strategies and global convergence results for a group of vehicles with constant speed (motivated in part by the fixed average speed (relative to water) of the gliders during AOSN-II). We have also developed control strategies for networked vehicles with unstable dynamics.

We have made a number of contributions to the ONR Glider System Study. These include the following: Scaling rules for steady state glides; study of influence of modifications to hull, wing and tail design; new designs, e.g., flying wings, new shapes, changing shapes; scaling rules for glider dynamics, for example, roll, pitch and turning rates, stability margins, control authority, etc.; evaluation of current glider controller designs and future prospects. A separate report has been prepared by Scott Jenkins summarizing the ONR Glider System Study.

RESULTS

A method was developed for glider system identification in the presence of a great number of uncertainties, e.g., drag coefficients and buoyancy trim offset. This method has the potential for use in trimming a glider at the beginning of deployment and in detecting system changes in the glider during deployment.

A method was developed for analyzing stability for nonlinear glider dynamics using the original phugoid mode equations. This method has the potential for development into a systematic glider control design technique.

Network control strategies for a fleet of vehicles have been developed that address issues that are important for glider control, notably global convergence properties in the case of constant speed vehicles. These strategies provide a new capability for glider networks.

We demonstrated the ability to coordinate the motion of a fleet of underwater gliders in a dynamic, uncertain ocean environment (Monterey Bay).

IMPACT/APPLICATIONS

The analysis and design methodology that we are developing for underwater glider dynamics and control will lead to a deeper understanding of how best to take advantage of the glider concept for ocean applications such as ocean sensing. Gliders have many useful features including low operational and capital costs, low noise and vibration, high reliability due to simplicity of design, minimal reliance on battery power, and low vulnerability of actuator mechanisms to the harsh effects of seawater. These features contribute to making the glider an economical, endurance ocean vehicle.

The advantages are expected to be greatest when multiple gliders are operated cooperatively in a network. With robust individual glider control and coordinating control design it is possible that networks of gliders can achieve highly efficient and adaptive group capabilities. This could lead to improved data-processing and decision-making capabilities which could have a major impact on missions such as adaptive ocean sampling.

TRANSITIONS

Modifications to the Slocum glider control software were incorporated by Webb Research Corp.

RELATED PROJECTS

I participate in an NSF/KDI funded project joint with A.S. Morse (Yale), P. Belhumeur (Yale), R. Brockett (Harvard), D. Grunbaum (U. Washington) and J. Parrish (U. Washington) on coordination of natural and man-made groups. We are studying schooling of fish and "schooling" of autonomous underwater vehicles. A multiple-vehicle experimental testbed has been developed at Princeton. This project is related to the problem of coordination of groups of underwater gliders. See http://graham.princeton.edu/~auvlab/ and http://www.eng.yale.edu/grouper/

I participate in an AFOSR funded project on Coordinated Control of Groups of Vehicles. This is a joint project with V. Kumar and J. Ostrowski at University of Pennsylvania. A focus of the project is on understanding cooperation in the context of coordinated control of distributed, autonomous agents, and the collection and fusion of the sensor information that they retrieve.

I am working on controlling autonomous underwater vehicles with internal actuation as part of a project on stabilization of mechanical systems using controlled Lagrangians. This is a joint project with A.M. Bloch (U. Michigan), J.E. Marsden (Caltech), D.E. Chang (UCSB) and C.A. Woolsey (Virginia Tech).

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HONORS/AWARDS/PRIZES

N.E. Leonard, Princeton University, Plenary lecture at the Society of Industrial and Applied Mathematics (SIAM)’s Conference on Applications of Dynamical Systems, May 2003.